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Measurement and improvement of bit error rate in 16QAM using laser hydrophones

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Abstract
At present, piezoelectric hydrophones are primarily employed in underwater acoustic communications. However, conventional hydrophones require direct contact with the acoustic field to detect the ultrasound. Consequently, they are unsuitable for environments with high bubble concentrations or water flow unless complex optical systems are employed. To address this limitation, a laser hydrophone based on the self-coupling effect of semiconductor lasers was proposed. This study explores the application of laser hydrophones in underwater acoustic communication. To achieve this objective, we previously conducted detection experiments with fundamental digital modulation methods such as Frequency Shift Keying, Amplitude Shift Keying, and Phase Shift Keying.
In this study, we extend the study to 16 Quadrature Amplitude Modulation, which incorporates both phase and amplitude modulation components. We aim to demonstrate the detection of its digital modulation waveforms and the measurement of BER. In addition, the characteristics obtained with visible and infrared lasers are compared to identify the optimal laser conditions for detecting 16QAM signals.

Acoustic, Laser, Measuring instrument, Sensor

1. Introduction

At present, underwater wireless communication in seawater is primarily based on underwater acoustic communication (UWAC), which employs ultrasonic waves rather than radio or optical waves because of their lower attenuation and ability to transmit information over long distances [1,2].

UWAC signals are mainly transmitted and received using piezoelectric hydrophones as transducers. However, piezoelectric hydrophones exhibit frequency response and directivity characteristics arising from the resonance of piezoelectric elements. In addition, because the sensing surface must be in direct contact with the acoustic field, it is highly susceptible to disturbances such as turbulence and bubbles [3,4].

These issues can be solved by an acoustic sensor that applies the self-coupling effect of a semiconductor laser (LD: Laser Diode). By utilizing the self-coupling effect, a compact and low-cost system configuration can be realized [5]. The self-coupling effect has mainly been used to measure the distance and velocity of a target, as well as for acoustic sensing applications. When this principle is applied to underwater acoustic detection, the device is referred to as a laser hydrophone.

This study aims for apply laser hydrophones to underwater acoustic communication. In particular, this paper compares the bit error rate (BER) obtained when digitally modulated waveforms, especially 16QAM, which is practically used in UWAC, are detected using a laser hydrophone at two wavelength bands with different water absorption coefficients.

2. Detection principle

The schematic diagram of an optical system exhibiting self-coupling is shown in Fig. 1. A continuously operating LD and a reflector are positioned facing each other, forming an external cavity between them. In a laser hydrophone, the water in a tank placed between the LD and reflector acts as an external cavity. Part of the reflected light returns to the active layer of the LD and interferes with the emitted light, causing variations in the optical output, which is referred to as the self-coupling effect.

Acoustic waves are density waves in a medium, and the refractive index changes owing to the compression and rarefaction caused by the acoustic wave. A laser hydrophone detects wavelength changes in the laser light induced by refractive index variations in the external cavity as phase changes in the self-coupling interference signal. The relationship between the refractive index of water, the laser wavelength, and the interference phase in the external cavity is shown in Fig. 2.

3. Experimental setup

The experimental setup is shown in Fig. 3. A 3M RP45 RED reflector (reflectivity 60%) was used. For the laser diode (LD), a ROHM RLD84PZJ2 was used for the infrared (IR) laser with a nominal emission wavelength of 840 nm, and a SHARP GH05280E2K was used for the visible (VIS) laser with a nominal emission wavelength of 520 nm. The lens and the semiconductor laser are mounted within a laser mount. The absorption coefficient of water at 840 nm is relatively high at 2.93×10^{-7}, whereas that at 520 nm is much lower at 1.32×10^{-9} [6].

The biconvex lens and LD are contained in a laser mount, and the water tank has a diameter of 300 mm. The laser mount and the tank, as well as the tank and the reflector, are installed in direct contact. The acoustic source (OKI OST2140) is placed 50 mm from the laser beam at a right angle. An ND filter is mounted on the reflector to maintain a reflectivity of 2×10^{-8}.

Five types of digital modulation schemes were used: FSK (Frequency Shift Keying), ASK (Amplitude Shift Keying), BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying), and 16QAM (16 Quadrature Amplitude Modulation). The fundamental frequency f_0 was set to 200 kHz, and the fundamental amplitude A_0 was 60 $V_{p\text{-}p}$. For FSK, a frequency deviation $\Delta f = 50$kHz was used, with the transmitted bit “0”

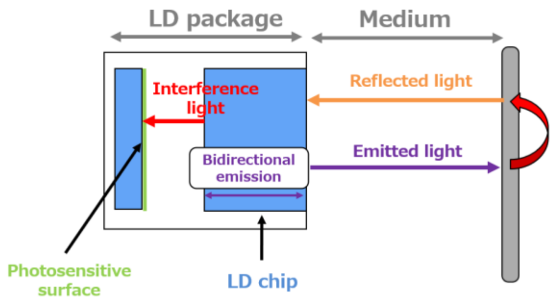

Figure 1. An optical system in which the self-coupling effect occurs.

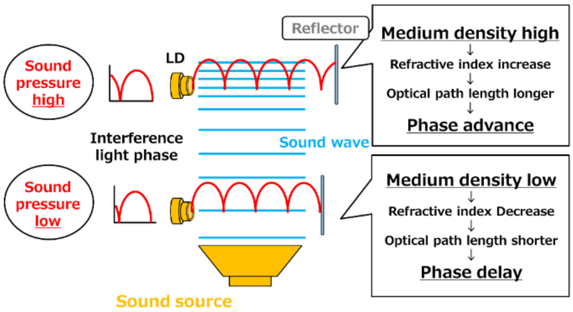

Figure 2. Relationship between refractive index, laser wavelength, and interference phase.

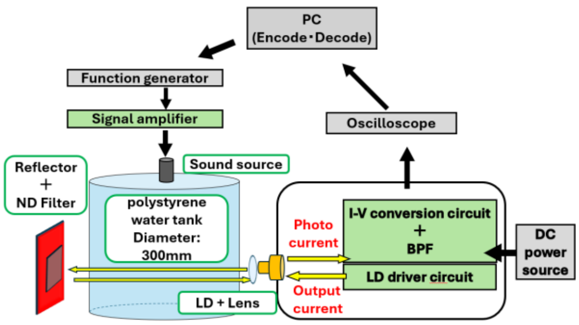

Figure 3. Experimental setup.

corresponding to a frequency of f_0 and the transmitted bit "1" corresponding to $f_0 + \Delta f$. For ASK, a modulation index of $m = 0.8$ was used, with the amplitude of the transmitted bit "1" set to $A_0$and that of bit "0" set to $(1-m)A_0$. In BPSK, the phase is inverted by 180° depending on whether the transmitted bit is "0" or "1". For QPSK, the phase is shifted by 90° increments corresponding to the transmitted bits "0", "1", "2", and "3". In 16QAM, every four bits are mapped to a single 16QAM symbol, with the upper two bits assigned to the in-phase (I) component and the lower two bits to the quadrature (Q) component. The amplitude levels of both I and Q components were mapped to $\{-3, -1, +1, +3\}$.

4. Results and discussion

The bit error rate (BER) measurement results for IR and VIS lasers at a laser power of 5 mW are shown in Table 1, and those at a laser power of 3 mW are shown in Table 2. From Tables 1 and 2, for all modulation schemes, the BER was lower at smaller laser power when using the VIS laser compared to the IR laser. Furthermore, when comparing the laser powers that yield the minimum BER for each of the IR and VIS lasers, the VIS laser exhibited a lower BER. Previous studies have shown that the noise intensity arising from the self-coupling effect depends on the intensity of the backward-emitted light from the active layer

Table 1. Experimental results (5 mW)

Modulation schemes	BER (IR Laser)	BER (VIS Laser)
ASK (m = 0.8)	11.8	9.8
ASK (m = 0.5)	12.4	12.9
FSK (Δf = 50 kHz)	1.5	2.1
FSK (Δf = 25 kHz)	5.1	6.8
BPSK	2.4	3.8
QPSK	3.4	4.1
16QAM	5.5	7.5

Table 2. Experimental results (3 mW)

Modulation schemes	BER (IR Laser)	BER (VIS Laser)
ASK (m = 0.8)	15.6	7.1
ASK (m = 0.5)	16.4	9
FSK (Δf = 50 kHz)	6.8	1
FSK (Δf = 25 kHz)	9.7	5.3
BPSK	3	2.3
QPSK	5.6	3.2
16QAM	8.4	5.1

of the semiconductor laser toward the detection surface, rather than the intensity of the reflected light. The results in Tables 1 and 2 can be attributed to the lower absorption of water at the wavelength of VIS laser, which allows sufficient reflected light intensity to be obtained even at lower laser powers with less noise arising from the backward-emitted light, thereby improving the BER.

5. Conclusion

In this study, to extend the applications of laser hydrophones, we attempted to detect 16QAM signals, which are widely used in underwater acoustic communication (UWAC). Five types of modulation schemes were employed, and the bit error rate (BER) was measured using two different laser powers and two wavelength bands. The results showed that the VIS laser achieved a lower BER than the IR laser, even at lower laser powers, and that overall BER was reduced. This improvement is attributed to the lower water absorption at the VIS laser wavelength, which allows sufficient reflected light intensity to be obtained at lower powers with lower noise, thereby improving BER performance.

Furthermore, in underwater acoustic communication, 64QAM (64-Quadrature Amplitude Modulation) is a practical digital modulation scheme that enables the transmission of more information per symbol. Future work will focus on implementing 64QAM, measuring its BER, and improving its performance. To date, experiments have been conducted under quiescent water conditions with minimal disturbance. To verify the effectiveness of the non-contact laser hydrophone, BER measurements under disturbed conditions will also be carried out in the future.

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